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ADAPTATION OF JET PUMPS FOR COMBINED
SUCTION AND BLOWING ON AN AIRPLANE WING

J.P. Chevallier and P. Jousserandot

As Translated by

H.B. Helmbold

Engineering Study No. 126

for the Office of Naval Research
Contract N-onr 201(01)



December 1953
University of Wichita
School of Engineering
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SUMMARY

The use of jet pumps for combined suction and blowing of the boundary layer permits solution of the difficult problem of uniform quantity distribution along the span of an airplane wing.

The low efficiency of jet pumps is compensated by their ease of installation, their lightness and safety of operation when using a source of compressed gas aboard the airplane.

For the study of the adaptation of jet pumps to combined suction and blowing one has to be contented with an approximate but handy theory, restricted by the reservations formulated by Maurice Roy (ref. 1). For the summary review of this theory we adopt its form used by Mac Clintock (ref. 2) in order to facilitate the use of experimental values of certain coefficients given by the latter. In this way it is feasible to perform computations for a jet pump adapted to suction (which imposes a quantity condition), to blowing (which imposes a momentum flux condition) or to any combination of both effects.

1. Notations (see fig. 1).

C''_p pressure coefficient $C''_p = \frac{\Delta p''}{\rho' V'^2/2}$

g gravitational acceleration $g = 9.81 \text{ m/s}^2$

K ratio of momentum fluxes at the diffuser end and at the injector: $K = \frac{q_m \cdot V}{q'_m \cdot V'}$

p_a atmospheric pressure

p_1 total pressure of the impellant

p_t total pressure

p static pressure

q_m, q_p, q_v mass, weight, volume delivered per unit time

q_u quantity per unit area: $q_u = \frac{q}{s}$

*Adaptation des trompes à induction assurant l'aspiration et le soufflage combinés sur une aile d'avion. La Recherche Aéronautique 35, p. 25 (1953).

S area of a cross section

V velocity

The primes ' and '' refer to the impelling jet and to the induced flow, respectively. The notations with no prime refer to the discharge section of the diffuser.

α Area of the discharge section of the diffuser, $\alpha = \frac{S}{S_m}$
area of the mixing-tube cross section

$\Delta p''$ pressure increase imparted to the secondary mass by the jet: $\Delta p'' = p_a - p_t''$

η_a suction efficiency: $\eta_a = \frac{q' \Delta p''}{q_m V^2 / 2}$

η_D diffuser efficiency

λ Area of the mixing-tube cross section: $\lambda = \frac{S_m}{S'}$
Area of the injector orifice

μ mass ratio: $\mu = \frac{q_m''}{q_m'}$

ρ density

σ density ratio induced to impelling air: $\sigma = \frac{\rho''}{\rho'}$

X adaptation coefficient weighted for suction-blowing:

$$(1+w)X = K+w \frac{q_m'' V''}{q_m' V''} = \frac{q_m V + w q_m' V''}{q_m' V'}$$

w weighting coefficient

2. Simplified Theory of Jet Pumps at Steady Flow.

2.1. Description of the jet pump.

A jet pump (fig. 1) consists of the following components:

- a) one or more injectors furnishing the primary inducing jet,
- b) a collecting mouth AB,
- c) a mixing tube BC,
- d) a diffuser CD.

On restriction to the case of a cylindrical mixing tube of a length proportional to its diameter * two geometrical parameters are sufficient to characterize the jet pump.

*The length of the mixing tube must be sufficient to secure the equalization of the velocities at the discharge of the jet pump: experience shows, e.g., that, for a jet pump with single injector, this length must be equal at least to 5 times the mixing-tube diameter.

The operation of the jet pump is defined by the following parameters:

$$\lambda = \frac{S_m}{S'} \text{ and } \alpha = \frac{S}{S_m},$$

μ , mass ratio, the ratio of secondary mass flux to primary mass flux, $\mu = \frac{q_m''}{q_m'}$,

K , thrust coefficient, ratio of the momentum flux at the diffuser discharge to the momentum flux at the injector orifice, $K = \frac{q_m V}{q_m' V'}$

$C''_{p'}$, pressure coefficient, ratio of the total-pressure increase of the secondary flow to the dynamic pressure of the primary jet, $C''_{p'} = \frac{\Delta p''}{\rho' V'^2 / 2}$

2.2. Establishment of the general jet-pump equation (ref.2).

The suppositions made in this calculation are
 - incompressibility of the induced and the discharged flow,
 - negligible frictional losses at the mixing-tube walls.
 The energy exchange between primary and induced flow is performed with equalization of the velocities: therefore it is analogous to the 'weak shock' (conservation of the momentum sum).

The total compression effected by the jet pump is

$$\Delta p'' = p_D - p_A = (p_D - p_C) + (p_C - p_B) - (p_A - p_B)$$

with $p_A - p_B = \frac{1}{2} \rho'' V_B''^2$ in the collecting mouth,

$$p_C - p_B = \frac{1}{S_m} (q_m' V_B' + q_m'' V_B'' - q_m V_C) \text{ in the mixing tube (conservation of momentum),}$$

$$p_D - p_C = \eta_D \frac{1}{2} \rho (V_C^2 - V_D^2) \text{ in the diffuser, when } \rho_C \approx \rho_D \text{ is assumed and } \eta_D \text{ denotes the diffuser efficiency.}$$

Referring all of the quantities to the primary jet the following equations are obtained:

$$p_A - p_B = \frac{\rho' V'^2 \mu^2}{2\sigma(\lambda-1)^2},$$

$$p_C - p_B = \frac{\rho' V'^2}{2} \frac{2}{\lambda} \left[1 + \frac{\mu^2}{\sigma(\lambda-1)} - \frac{(1+\mu)(1+\frac{\mu}{\sigma})}{\lambda} \right],$$

$$p_D - p_C = \frac{\rho' V'^2}{2} \frac{\eta_D}{\lambda} (1+\mu) \left(1 + \frac{\mu}{\sigma} \right) \left(1 - \frac{1}{\alpha^2} \right).$$

Hence the general equation

$$C''_{p'} = \frac{\Delta p''}{\rho' V'^2/2} = \frac{2}{\lambda} \left[\frac{1-k(1+\mu)(1+\frac{\mu}{\sigma})}{\lambda} + \frac{(\lambda-2)\mu^2}{2\sigma(\lambda-1)^2} \right] \quad (1)$$

$$\text{with } k = 1 - \frac{\eta_D}{2} \left(1 - \frac{1}{\alpha^2} \right). \quad (2)$$

Reference 2 contains this equation, in a similar form, as well as experimental values of the coefficient k .

For a given jet pump (α and λ constant), this equation (1) furnishes a characteristic $C''_{p'}(\mu)$ as represented by fig. 2. Another characteristic, pressure loss as a function of weight flux, $\Delta p''(q_p'')$, is obtained by introducing the dynamic pressure $\rho' V'^2/2$ and the weight flux q_p' of the primary jet, as a function of the total pressure p_1' of the impellant, supposing an isentropic expansion up to the mixing section (fig. 3).

In the case of a given jet pump aspirating through a variable pressure loss the point of operation is displaced in the characteristic $C''_{p'}(\mu)$ as a function of this pressure loss.

When the primary jet is supersonic the effective cross section of the primary jet (after complete expansion to the mixing-tube pressure) becomes a function of the initial total pressure of the impellant; thence a variation of the parameters μ and σ results which modifies the characteristic $C''_{p'}(\mu)$ with no discontinuity of operation; experience confirms that μ decreases when the total pressure p_1' increases over the critical pressure corresponding to sonic speed at the jet orifice.

3. Adaptation of a Jet Pump to Suction.

Defining the proper suction efficiency η_a as the ratio of the suction power $q_p'' \Delta p''$ to the kinetic power of the primary jet $q_p' V'^2/2$ gives

$$\eta_a = \frac{q_p'' \Delta p''}{q_p' V'^2/2} = \frac{\mu C''_{p'}}{\sigma}.$$

The adaptation of a jet pump to suction consists in securing a maximum value to the efficiency η_a , compatible with the given quantities p_1' and $\Delta p''$, that means searching for a maximum μ at constant $C''_{p'}$.

The characteristics $C''_{p'}(\mu)$ constitute a family of curves as a function of λ which has a curve $\Gamma(\alpha)$ for an envelope (fig. 2). The point of tangency of an individual characteristic (for given λ and α) with this envelope is the point of optimum operation of the corresponding jet pump. When α increases, the suction efficiency increases too, but the value of η_D limits this gain.

By use of the approximation (to the term in $\frac{1}{\lambda^3}$)

$$\frac{(\lambda-2)\mu^2}{2\sigma(\lambda-1)} \approx \frac{\mu^2}{2\sigma\lambda}$$

equation (1) can be written

$$C''_{p1} = \frac{2}{\lambda^2} \left[\lambda - k(1+\mu)\left(1+\frac{\mu}{\sigma}\right) + \frac{\mu^2}{2\sigma} \right], \quad (3)$$

and the equation of the envelope $\Gamma(\alpha)$ is obtained by putting the discriminant of equation (3) equal to zero (second degree in λ):

$$C''_{p1} = \frac{1}{2k(1+\mu)\left(1+\frac{\mu}{\sigma}\right) - \frac{\mu^2}{\sigma}} \quad (4)$$

The point of tangency with the envelope is given by the double root $\lambda = 1/C''_{p1}$.

Since $C''_{p1} = 1/\lambda$ holds for any point of the envelope Γ , the adaptation of the jet pump to a given pressure coefficient is independent of α . The parameter α leaves a certain freedom for the choice of the discharge cross section S and the mass ratio μ .

4. Adaptation of a Jet Pump to Momentum Conservation.

Let K denote the ratio of the momentum fluxes at the discharges of the diffuser and of the injector, $K = q_m V / q'_m V'$. It is required to determine λ and α to give this ratio its maximum value compatible with the imposed pressure coefficient C''_{p1} .

Neglecting the differences of velocity-profile shape (which can be accounted for by an experimental coefficient) the ratio can be written

$$K = (1+\mu) \frac{1 + \frac{\mu}{\sigma}}{\alpha\lambda}. \quad (5)$$

By eliminating μ the equations (1) and (5) define a family of surfaces for constant α in the space (K, C''_{p1}, λ) . Their contour projected on the plane (K, C''_{p1}) plays a role analogous to the envelope Γ for adaptation to suction, considered previously.

As an example, fig. 5 shows the course of the characteristics (C''_{p1}, K) and their envelope for the simple case when $\sigma = \alpha = \lambda = 1$.

Generally this adaptation leads to lower values of λ than the value of λ determined by adaptation to suction (adaptation curve λ_K in fig. 7).

5. Adaptation of a Jet Pump to Combined Suction and Blowing for Circulation Control.

The experiments on circulation control have shown the role played by the momentum flux of the blowing jet $q_m V$ and the suction quantity q_v'' , respectively. Now we present a criterion of adaptation which leads us to a solution intermediate between the solutions discussed previously, viz. adaptation to suction only and adaptation to blowing only. The suction quantity will be accounted for by a fictitious momentum flux defined by $q_m'' V''$ with $\rho V''^2/2 = \Delta p''$.

Let w denote a weighting coefficient; the tests on circulation control will permit defining for any case the optimum value of w according to the required goal: power loading or lift-drag ratio on the take-off conditions of an airplane driven by propeller or jet, CL_{max} on the landing conditions. For example, by varying the suction and the blowing simultaneously and independently, the quantity to be made a maximum for a constant total power ($q_v \Delta p + q_v'' \Delta p''$) can be determined as a function of w .

After selection of the average value of w corresponding to the various utilized flight configurations it is introduced into the adaptation criterion defined by

$$X = \frac{K+wK''}{1+w} \text{ with } K'' = \frac{q_m'' V''}{q_m' V'}, K = \frac{q_m V}{q_m' V'},$$

where w corresponds to the optimum (K''/K). Hence, in terms of jet-pump parameters,

$$(1+w)X = \frac{(1+\mu)(1+\frac{\mu}{\alpha})}{\alpha\lambda} + w\mu \sqrt{\frac{C''_{p'}}{\sigma}}. \quad (6)$$

In combination with equation (1) this equation permits drawing the curve of adaptation $C''_{p'}(\lambda, X)$ for a given α , as before. For example, fig. 6 presents the determination of this curve for $w = 1$ and $\sigma = \alpha = k = 1$ (characteristics $(C''_{p'}, X)$ and their envelope). The adaptation curve (fig. 7) furnished by the points of tangency of the envelope is situated between the adaptation curves for suction ($\lambda = 1/C''_{p'}$) and for momentum conservation ($\lambda_K, C''_{p'}$); it may be remarked that only the adaptation to suction is independent of α .

6. Example of Calculation of a Jet Pump Adapted to Suction.

6.1. Given

- the total pressure of the impellant $p_1' = 20,410 \text{ kg/cm}^2$,
- the suction quantity $q_p'' = 0.750 \text{ kg/s}$,
- the law of pressure loss as a function of suction quantity

$$q_p'' = f(\Delta p''); \Delta p'' = 1860 \text{ kg/m}^2 \text{ for } q_p'' = 0.750 \text{ kg/s},$$

- the ratio $\sigma = \rho''/\rho' \cong 0.75$ (obtained from p_1').

The equation connecting the various parameters is (1). with (2). Supplementary condition: it is required to adapt the jet pump to the maximum suction efficiency

$$\eta_a = \left(\frac{C'' p_1' \mu}{\sigma} \right) \text{ maximum, hence } C'' p_1' = \frac{1}{\lambda}.$$

The unknowns are λ and α , hence S' , S_m , S and q' .

6.2. Course of Calculation.

From the total pressure p_1' ,

$q_u' = 0.048 \text{ kg/s/cm}^2 =$ isentropic quantity per unit area, and

$$\frac{\rho' V'^2}{2} = 7700 \text{ kg/m}^2 = \text{dynamic pressure of the primary jet.}$$

On the other hand

$$C'' p_1' = \frac{\Delta p''}{\rho' V'^2/2} = \frac{1860}{7700} = 0.241.$$

Hence the geometrical parameter

$$\lambda = \frac{1}{C'' p_1'} = \frac{1}{0.241} = 4.15.$$

Now the coefficient α and the discharge cross-section remain to be determined. In equation (1) $C'' p_1'$, λ and $\sigma \cong 0.75$ (for $p_1' = 20410 \text{ kg/m}^2$) are given and K depends on α . Thus we obtain a curve (μ, α) , fig. 4. Then we compute

$$q_p' = \frac{q_p''}{\mu}$$

$$S = \frac{q_p'}{q_u'}, \quad q_u' \text{ being the mass flux per unit orifice area of the injector,}$$

$$S_m = \lambda S',$$

$$S = \alpha S_m.$$

The curve $S(\alpha)$ is plotted in fig. 4; S is chosen compatible with the dimensions to be considered for the discharge of the jet pump (here $S = 150 \text{ cm}^2$). There result two values of α corresponding to $S = 150 \text{ cm}^2$. The value of α which corresponds to maximum μ is adopted since η_a maximum is required ($\alpha = 1.69$ is chosen, hence $\mu = 0.73$).

The second value of α ($\alpha = 1.3$) corresponds to a better conservation of the primary-jet thrust ($K = 0.564$ instead of 0.522), but to a suction efficiency diminished by about 20 % ($\mu = 0.57$ instead of 0.73).

Now the jet pump being completely determined, its theoretical characteristic $C''_{p_i}(\mu)$ can be calculated as well as a portion of its envelope (fig. 2), for $\alpha = 1.69$,

$$C''_{p_i} = \frac{1}{2k(1+\mu)(1 + \frac{\mu}{\sigma}) - \frac{\mu^2}{\sigma}}.$$

It may be observed that for a different value of α the pressure-increase coefficient of adaptation C''_{p_i} doesn't change (there is always $C''_{p_i} = 1/\lambda = 0.241$) and that only the mass ratio μ varies with α ; in other words, the locus of the points of tangency between envelopes and characteristics is the straight line of the ordinate $C''_{p_i} = 0.241$.

On the other hand, the experiment has furnished us the curves $(\Delta p'', q_p'')$, fig. 3, for different pressure losses obtained by grids at the collecting mouth (fig. 1). Thence an experimental characteristic (fig. 2) was deduced; the point of adaptation according to theory (point of tangency between envelope and characteristic $C''_{p_i} = 1/\lambda = 0.241$) would correspond to a higher pressure loss than obtained experimentally. However, fig. 2 establishes that the theoretical and experimental characteristics are very close together.

7. Conclusions.

Experience shows that the simplified theory, as illustrated by the preceding example of a jet pump adapted to suction, is of sufficient validity for a reasonable determination of the geometrical parameters and the characteristics of operation.

The optimum utilization of jet pumps for combined suction and blowing on an airplane wing is still defined rather poorly; experimental research of the exterior aerodynamics is still necessary to determine especially the importance of suction and blowing for the problems of increasing lift by boundary-layer control.

The best method would be to study separately the influence of suction quantity, on the one hand, and of momentum, on the other hand; the experiment should be performed with an airfoil in plane flow at a Reynolds number close to reality; the suction and blowing slots, of controllable width and shape, would be charged by two separate pumps, and for any flight configuration (cruising, landing, or take off) the quantities needed for reattachment of the boundary layer over the whole profile would be explored.

Starting from these data and the pressure characteristics at intake and discharge of the jet pump it would be feasible, by the above method to compute an 'optimum' jet pump designed to satisfy simultaneously the conditions of suction and blowing.

References.

1. Maurice Roy, Tuyères, trompes, fusées et projectiles, problèmes divers de dynamique de fluides aux grandes vitesses. P.S.T. 203
2. Mac Clintock, Aircraft ejector performances. J.A.S. Nov. 1946.

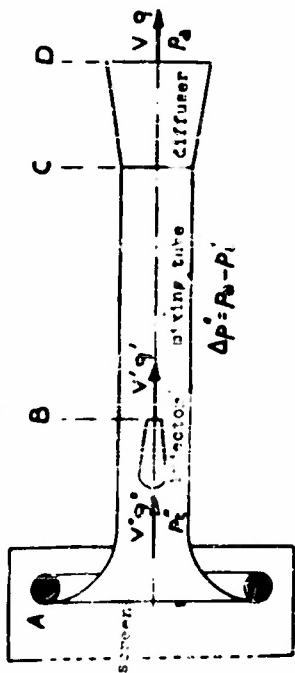
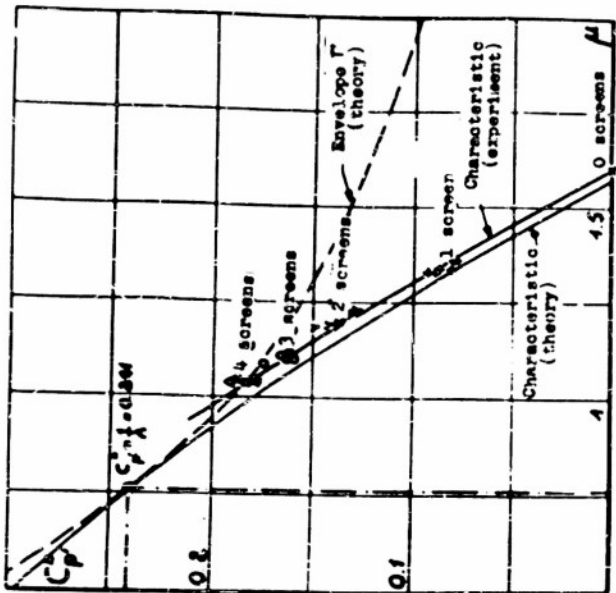


Figure 1.- Sketch of the jet-pump principle



2.- Theoretical and experimental characteristics

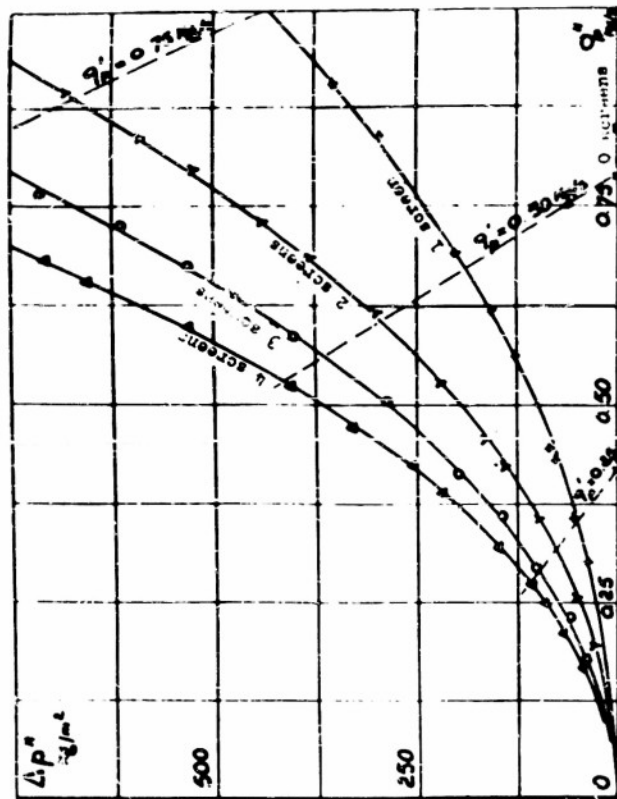


Figure 2.- Suction characteristics at variable pressure losses

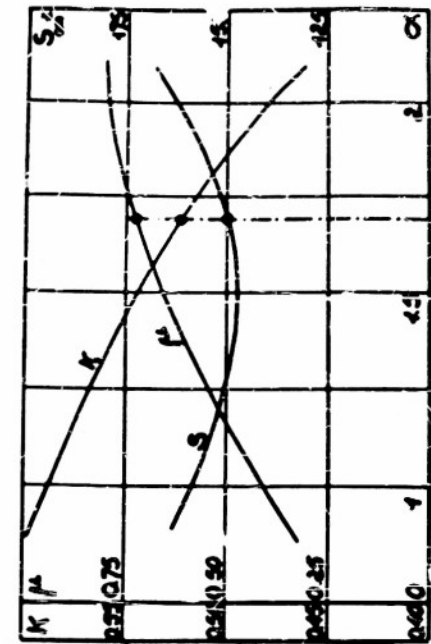


Figure 4.- Determination of the parameter a

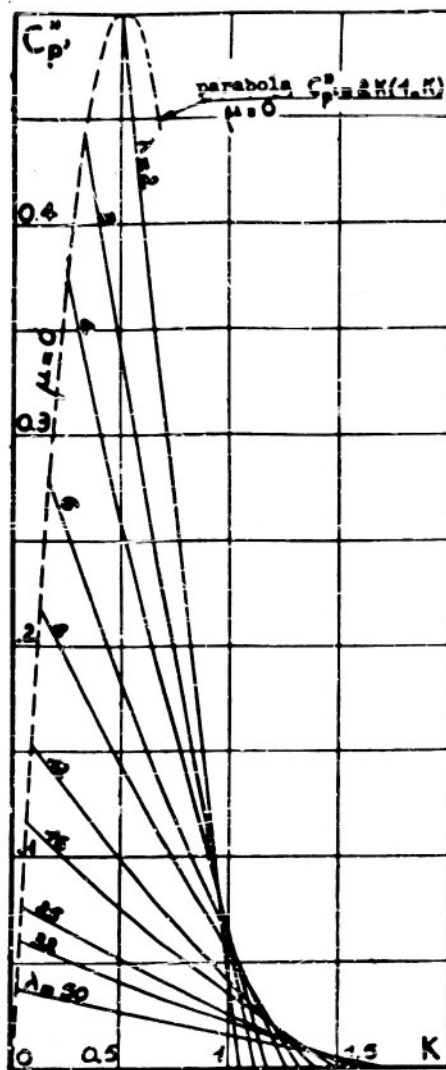


Figure 5.- Adaptation to conservation of momentum

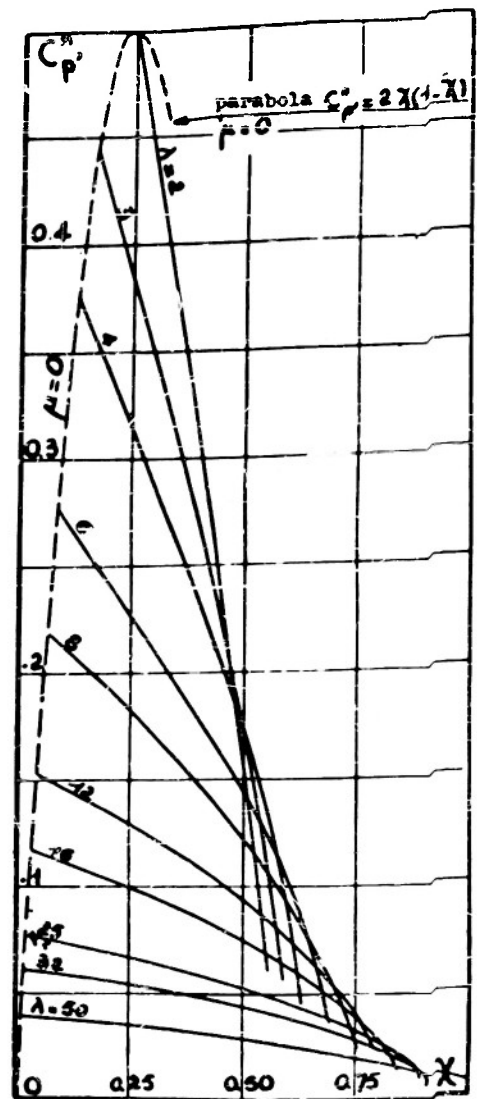


Figure 6.- Adaptation to suction and blowing

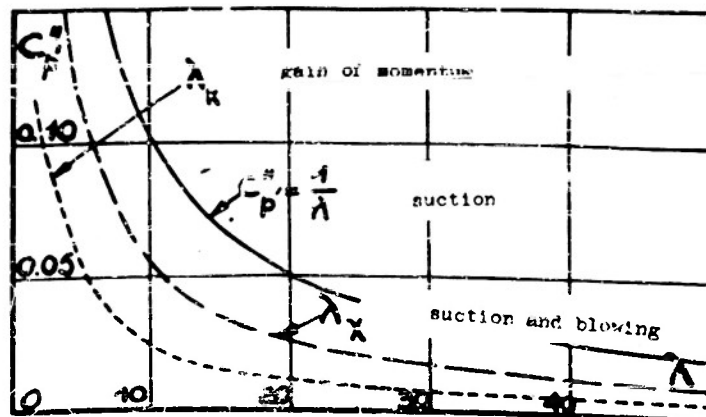


Figure 7.- Parameters of tangency (envelopes and characteristics)

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